

$pp \rightarrow pp\omega$ reaction near threshold

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Abstract

We analyze the total cross section data for $pp \rightarrow pp\omega$ near threshold measured recently at SATURNE. Using an effective range approximation for the on-shell pp S-wave final state interaction we extract from these data the modulus $|\Omega| = 0.53 \text{ fm}^4$ of the threshold transition amplitude Ω . We present a calculation of various (tree-level) meson exchange diagrams contributing to Ω . It is essential that ω -emission from the anomalous $\omega\rho\pi$ -vertex interferes destructively with ω -emission from the proton lines. The contribution of scalar σ -meson exchange to Ω turns out to be negligibly small. Without introducing off-shell meson-nucleon form factors the experimental value $|\Omega| = 0.53 \text{ fm}^4$ can be reproduced with an ωN -coupling constant of $g_{\omega N} = 10.7$. The results of the present approach agree qualitatively with the Jülich model. We also perform a combined analysis of the reactions $pp \rightarrow pp\pi^0$, $pn\pi^+$, $pp\eta$, $pp\omega$ and $pn \rightarrow pn\eta$ near threshold.

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Meson production in nucleon-nucleon collisions is considered to provide important information on the NN-interaction at short distances due to the necessarily large momentum transfers involved in such reactions. There is an on-going experimental program at the proton cooler synchrotrons IUCF (Bloomington), CELSIUS (Uppsala) and COSY (Jülich) to measure in detail various mesonic final states (π , $\pi\pi$, K , η , ω , ϕ , η'). In the energy region near threshold the theoretical interpretation of the meson production process is expected to simplify considerably since only few transitions (mainly those with S-waves in the final state) will contribute.

In a recent work [1, 2] we have developed a novel (and rather simple) approach to meson production in proton-proton collisions, $pp \rightarrow pp\pi^0$, $pn\pi^+$, $pp\eta$, $p\Lambda K^+$, near threshold. One starts from the invariant T-matrix at threshold in the center-of-mass frame which is parameterized in terms of one (or two) constant threshold amplitudes. Close to threshold the relative momentum of the nucleons in the final state is very small and their empirically known strong S-wave interaction plays an essential role in the description of the meson-production data (see also ref.[3]). In fact it was found in refs.[1, 2] that in all

cases the energy dependence of the total cross section near threshold is completely and accurately determined by the three-body phase space and the on-shell S-wave final state interaction. Close to threshold the final state interaction can even be treated in effective range approximation using the well-known values of the scattering lengths and effective range parameters. Note that ref.[1] gives a (partial) derivation of such an approach to final state interaction in the context of effective field theory (i.e. using only Feynman diagrams). Once one accepts such a phenomenological separation of the (on-shell) final state interaction from the full production process, one can extract from the total cross section data an experimental value of the constant threshold amplitude parameterizing the T-matrix. In the next step a standard (relativistic) Feynman diagram calculation is performed for the center-of-mass T-matrix at threshold. As a major result it was found in refs.[1, 2] that already the well-known tree-level (pseudoscalar and vector) meson exchange diagrams lead to predictions for the constant threshold amplitudes which agree with the corresponding experimental values within a few percent.

The purpose of this brief report is to present a similar analysis for the ω -meson production channel $pp \rightarrow pp\omega$. For this reaction total cross section data near threshold have been measured recently by the SPES3 collaboration at SATURNE [4] and further data are expected to come soon from COSY. Theoretical calculations of ω -production in pp -collisions have been performed within the Jülich meson exchange model of hadronic interactions in refs.[5, 6]. We will consider here the same ω -production mechanisms as in refs.[5, 6]. However, since our approach is entirely analytical it allows in a very transparent way to study the role of various meson exchanges and their sensitivity to the coupling constants.

The T-matrix for omega-meson production in proton-proton collisions $p_1(\vec{p}) + p_2(-\vec{p}) \rightarrow p + p + \omega$ at threshold in the center-of-mass frame reads

$$T_{\text{th}}^{\text{cm}}(pp \rightarrow pp\omega) = \Omega (i \vec{\sigma}_1 - i \vec{\sigma}_2 + \vec{\sigma}_1 \times \vec{\sigma}_2) \cdot (\vec{\epsilon} \times \vec{p}) , \quad (1)$$

where $\vec{\epsilon}$ denotes the ω -meson polarization vector and \vec{p} is the proton center-of-mass momentum with $|\vec{p}| = 941.6$ MeV at threshold. $\vec{\sigma}_1$ and $\vec{\sigma}_2$ are the spin-operators of the two protons. The (complex) threshold amplitude Ω (of dimension fm⁴) belongs to the transition ${}^3P_1 \rightarrow {}^1S_0 s_1$. Of course the ω -meson couples to a conserved current, however, for the threshold kinematics this feature does not imply any constraints on eq.(1). We follow now the successful approach to π - and η -production of ref.[1] and assume the T-matrix to be constant in the near threshold region and the energy dependence of the total cross section to be given by three-body phase space and (on-shell) pp S-wave final state interaction. In this case the unpolarized total cross section for $pp \rightarrow pp\omega$ including pp S-wave final state interaction reads

$$\begin{aligned} \sigma_{\text{tot}}(Q) &= |\Omega|^2 M^4 \frac{\sqrt{(Q + m_\omega)(Q + 4M + m_\omega)}}{[2\pi(Q + 2M + m_\omega)]^3} \\ &\times \int_{2M}^{2M+Q} dW \sqrt{(W^2 - 4M^2) \lambda(W^2, m_\omega^2, (Q + 2M + m_\omega)^2)} F_p(W) , \quad (2) \end{aligned}$$

with Q the center-of-mass excess energy. W is the final state di-proton invariant mass and $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2yz - 2xz - 2xy$ denotes the conventional Källén function. $M = 938.3$ MeV and $m_\omega = 782$ MeV stand for the proton and ω -meson mass. The correction factor $F_p(W)$ due to the strong pp S-wave final state interaction reads in effective

range approximation

$$F_p(W) = \left[1 + \frac{a_p}{4}(a_p + r_p)(W^2 - 4M^2) + \frac{a_p^2 r_p^2}{64}(W^2 - 4M^2)^2 \right]^{-1}, \quad (3)$$

with the empirical scattering length $a_p = 7.81$ fm and effective range parameter $r_p = 2.77$ fm taken from ref.[7]. Using eqs.(2,3) for the total cross section, a best fit to the five SATURNE data points [4] near threshold ($Q \leq 31$ MeV) gives for the modulus of the threshold amplitude

$$|\Omega| = 0.53 \text{ fm}^4, \quad (4)$$

with a small total $\chi^2 = 2.5$. The resulting fit values of σ_{tot} are given in table 1 and the energy dependent cross section is shown in Fig. 1 for excess energies $Q \leq 34$ MeV.

Q [MeV]	3.8	9.1	14.4	19.6	30.1
$\sigma_{\text{tot}}^{\text{exp}} [\mu\text{b}]$	0.32 ± 0.08	0.70 ± 0.14	1.07 ± 0.25	1.51 ± 0.30	1.77 ± 0.55
$\sigma_{\text{tot}}^{\text{fit}} [\mu\text{b}]$	0.23	0.67	1.11	1.54	2.36

Tab. 1: Total cross sections for $pp \rightarrow pp\omega$. The data are taken from ref.[4] and the fit is described in the text.

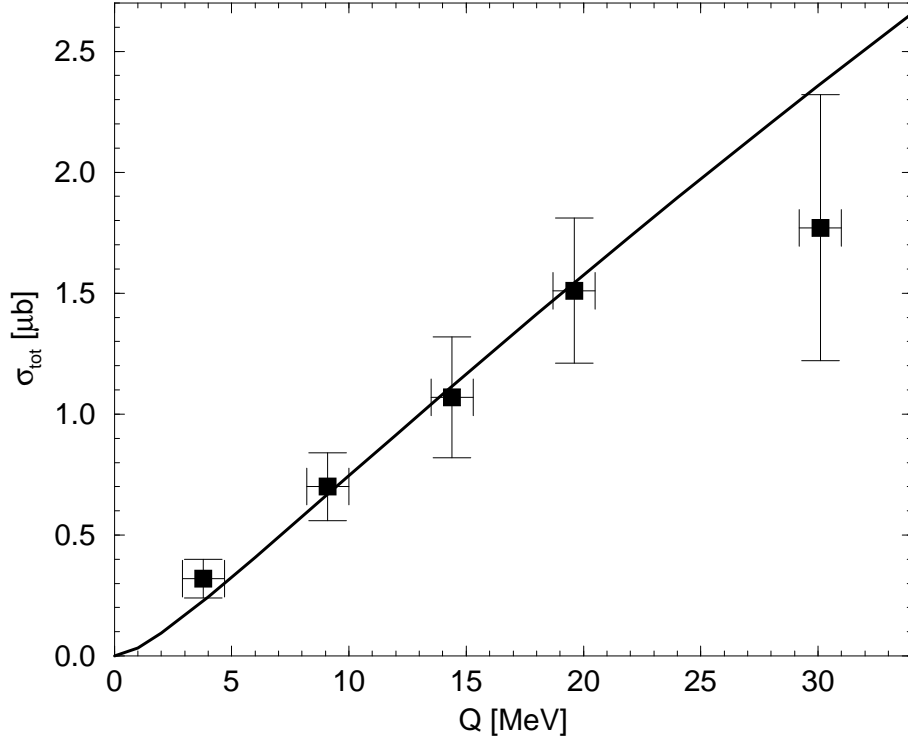


Fig. 1: Total cross sections for $pp \rightarrow pp\omega$ as a function of the center-of-mass excess energy Q . The data are taken from ref.[4] and the full line is calculated with $|\Omega| = 0.53 \text{ fm}^4$ and pp S-wave final state interaction. The experimental uncertainty of Q is ± 0.9 MeV.

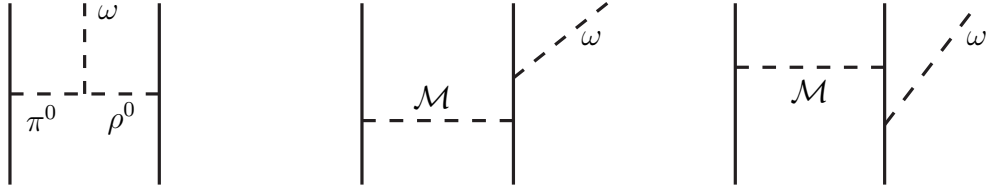


Fig. 2: Meson exchange diagrams ($\mathcal{M} = \pi^0, \eta, \omega, \rho^0, \sigma$) contributing to $pp \rightarrow pp\omega$. Graphs where the ω -meson is emitted from the other proton (solid) line and graphs with crossed outgoing proton lines are not shown.

The quality of reproducing the energy dependence of the data is comparable to the dynamical calculation of ref.[6] where the data point at $Q = 30.1$ MeV is also somewhat overestimated. In the context of the present approach one cannot expect the approximations eqs.(2,3) to be valid up to $Q = 30$ MeV. Note that in the case of $pp \rightarrow pp\pi^0$ [1] the analogous approach based on eqs.(2,3) has given a very good description of the total cross section data up to $Q = 21.3$ MeV.

Next we come to the evaluation of the diagrams shown in Fig. 2. We start with those graphs where the ω -meson is emitted from one proton line and a meson is exchanged between both protons. Their contributions to Ω evidently scale with the ωN -coupling constants. For the tensor-to-vector coupling ratio we use the value $\kappa_\omega = -0.16$ as found (with a small error bar) in a recent dispersion-theoretical analysis [8] of the nucleon electromagnetic form factors. The for our purpose optimal value of the ωN -coupling constant is $g_{\omega N} = 10.7$. Such a value of $g_{\omega N}$ is consistent with $g_{\omega N} = 10.1 \pm 0.9$ as obtained from forward NN-dispersion relations [9] and it is also not far from the one used in modern boson exchange NN-potentials [10]. We find from the π^0 -exchange diagrams

$$\Omega^{(\pi)} = \frac{g_{\omega N} g_{\pi N}^2 m_\omega}{4M^2(m_\pi^2 + Mm_\omega)(2M + m_\omega)} \left[1 - \kappa_\omega \left(1 + \frac{m_\omega}{M} \right) \right] = 0.42 \text{ fm}^4, \quad (5)$$

with $g_{\pi N} = 13.4$ the strong πN -coupling constant [7] and we used the pseudovector πNN -vertex. In the case of the pseudoscalar πNN -vertex the expression in the square bracket would be replaced by $1 + \kappa_\omega$. Similarly, we get from $\eta(547)$ -exchange

$$\Omega^{(\eta)} = \frac{g_{\omega N} g_{\eta N}^2 m_\omega}{4M^2(m_\eta^2 + Mm_\omega)(2M + m_\omega)} \left[1 - \kappa_\omega \left(1 + \frac{m_\omega}{M} \right) \right] = 0.04 \text{ fm}^4, \quad (6)$$

using the SU(3)-value of the ηN -coupling constant $g_{\eta N} = \sqrt{3}g_{\pi N}/5 = 4.64$ together with the simplified ratio of the octet axial vector coupling constants $D/F = 1.5$. Since this contribution is rather small the precise value of $g_{\eta N}$ does not matter here. Next, we find from ω -exchange

$$\begin{aligned} \Omega^{(\omega)} = & \frac{g_{\omega N}^3}{Mm_\omega(M + m_\omega)(2M + m_\omega)} \left[-\kappa_\omega + \frac{m_\omega}{4M} (2 + 2\kappa_\omega + \kappa_\omega^2 - 2\kappa_\omega^3) \right. \\ & \left. - \frac{m_\omega^2}{16M^2} \kappa_\omega^2 (3 + 5\kappa_\omega) \right] = 0.28 \text{ fm}^4, \end{aligned} \quad (7)$$

and from ρ^0 -exchange

$$\begin{aligned} \Omega^{(\rho)} = & \frac{g_{\omega N} g_{\rho N}^2}{M(m_\rho^2 + Mm_\omega)(2M + m_\omega)} \left[-\kappa_\omega + \frac{m_\omega}{4M}(2 + 2\kappa_\rho + \kappa_\rho^2 - 2\kappa_\rho^2 \kappa_\omega) \right. \\ & \left. + \frac{m_\omega^2}{16M^2} \kappa_\rho (\kappa_\rho - 4\kappa_\omega - 5\kappa_\rho \kappa_\omega) \right] = 0.74 \text{ fm}^4 . \end{aligned} \quad (8)$$

Here, we used $\kappa_\rho = 6.1$ as determined from the dispersion theoretical analysis [8] of the nucleon electromagnetic form factors and $g_{\rho N} = 3.04$. This value follows from the ρ -universality relation $g_{\rho N} = g_{\rho\pi}/2$ with $g_{\rho\pi} = 6.08$ as determined from the empirical $\rho \rightarrow \pi\pi$ decay width. The chosen value $g_{\rho N} = 3.04$ lies in between $g_{\rho N} = 2.63 \pm 0.14$ as obtained from πN -dispersion relations [11] and $g_{\rho N} = 3.25$ as employed in the NN-potential of ref.[10]. Furthermore, we consider a scalar σ -meson exchange and find

$$\Omega^{(\sigma)} = \frac{g_{\omega N} g_{\sigma N}^2}{M(m_\sigma^2 + Mm_\omega)(2M + m_\omega)} \left[\kappa_\omega + \frac{m_\omega}{4M}(1 + 3\kappa_\omega) \right] = -0.02 \text{ fm}^4 , \quad (9)$$

inserting the mass $m_\sigma = 550$ MeV and the coupling constant $g_{\sigma N} = 8.5$ taken from [12]. Even though the mass m_σ is rather low and the coupling constant $g_{\sigma N}$ is rather large, the contribution $\Omega^{(\sigma)}$ turns out to be negligibly small. Consequently, scalar meson exchanges do not play any significant role in ω -production near threshold. Obviously, one needs now a large negative contribution to cancel the large ρ^0 -exchange contribution $\Omega^{(\rho)}$. This can be generated by ω -emission from the anomalous $\omega\rho\pi$ -vertex

$$\mathcal{L}_{\omega\rho\pi} = -\frac{G_{\omega\rho\pi}}{f_\pi} \epsilon^{\mu\nu\alpha\beta} (\partial_\mu \omega_\nu) \vec{\rho}_\alpha \cdot \partial_\beta \vec{\pi} , \quad (10)$$

with $\epsilon^{\mu\nu\alpha\beta}$ the totally antisymmetric tensor in four dimensions ($\epsilon^{0123} = -1$) and $f_\pi = 92.4$ MeV the weak pion decay constant. Evaluation of the first diagram in Fig. 2 leads to

$$\Omega^{(an)} = \frac{g_{\pi N} g_{\rho N} (1 + \kappa_\rho) G_{\omega\rho\pi} m_\omega^2}{4M f_\pi (m_\pi^2 + Mm_\omega)(m_\rho^2 + Mm_\omega)} = -0.93 \text{ fm}^4 , \quad (11)$$

and we used $G_{\omega\rho\pi} = -1.2$ as determined (modulo the sign) in [13] from systematic studies of $\omega(782)$ - and $\phi(1020)$ -decays. This value of $G_{\omega\rho\pi}$ (including the sign) is equivalent to the one used in ref.[5], where also a large cancelation between the dominant $\omega\rho\pi$ -exchange current and nucleonic current contributions was found. Note that in our previous work [1] on $pp \rightarrow pp\pi^0$ we took a $G_{\omega\rho\pi}$ -value of positive sign as given by the Wess-Zumino-term for vector meson. This specific form of $\mathcal{L}_{\omega\rho\pi}$ which assumes a particular realization of vector meson dominance (with direct vector-meson-photon conversion) is, however, not mandatory and alternative derivations of a Lagrangian $\mathcal{L}_{\omega\rho\pi}$ have been given in ref.[14]. In any case the contribution of the $\omega\rho\pi$ -vertex to the $pp \rightarrow pp\pi^0$ threshold amplitude is very small (about 3%) and a sign change does not matter. Due to the large cancelation between $\Omega^{(\rho)}$ and $\Omega^{(an)}$ one observes a moderate dependence of total amplitude Ω on the ρN -coupling constant $g_{\rho N}$. Within the range mentioned above one finds variations of ± 0.05 fm⁴. The negative value of the tensor-to-vector coupling ratio $\kappa_\omega = -0.16$ is in fact crucial, setting $\kappa_\omega = 0$ the total sum of all contributions would be reduced to $\Omega = 0.30$ fm⁴. A similar strong dependence on κ_ω was observed in the Jülich model [5]. In contrast to [5, 6]

we see no need to introduce off-shell meson-nucleon form factors in order to reproduce the empirical value of $|\Omega| = 0.53 \text{ fm}^4$. The basic reason for this is that the final state interaction of ref.[5] leads to a strong enhancement of the total cross section near threshold, whereas it causes a strong reduction in the present approach based on eqs.(2,3) since $F_p(W) \leq 1$ (see appendix C in ref.[1]). For a discussion of the comparably small and more uncertain effects due to nucleon resonance excitation and other meson-exchange currents, see ref.[5].

Let us finally combine the results of ref.[1] for $pp \rightarrow pN\pi$ and $NN \rightarrow NN\eta$ with the ones obtained here for $pp \rightarrow pp\omega$ and search for a common set of coupling constants. For reasons of consistency we omit the small pion loop contribution $\mathcal{A}^{(loop)} = -0.14 \text{ fm}^4$ calculated in [1] and we complete the expressions for $\mathcal{A}^{(\omega)}$, $\mathcal{A}^{(\omega\rho\pi)}$, $\mathcal{B}^{(\omega)}$, $\mathcal{C}^{(\omega)}$ and $\mathcal{D}^{(\omega)}$ by the terms coming from the non-zero κ_ω . This amounts to very small changes of about 1% in the case $NN \rightarrow NN\pi$ and of about 5% in the case $NN \rightarrow NN\eta$. Furthermore, we disregard the small σ -meson exchange contribution $\Omega^{(\sigma)}$. With the coupling constants $g_{\pi N} = 13.4$, $g_{\rho N} = 3.04$, $\kappa_\rho = 6.1$, $\kappa_\omega = -0.16$ taken fixed and $g_{\omega N} = 9.8$, $g_{\eta N} = 5.22$, $G_{\omega\rho\pi} = -1.03$ being adjusted one obtains $\mathcal{A} = 2.74 \text{ fm}^4$, $\mathcal{B} = 2.69 \text{ fm}^4$, $\mathcal{C} = 1.32 \text{ fm}^4$, $\mathcal{D} = 1.86 \text{ fm}^4$, $\Omega = 0.53 \text{ fm}^4$ in comparison to the experimental values of $\mathcal{A} = (2.7 - 0.3 i) \text{ fm}^4$, $\mathcal{B} = (2.8 - 1.5 i) \text{ fm}^4$, $|\mathcal{C}| = 1.32 \text{ fm}^4$, $|\mathcal{D}| = 2.3 \text{ fm}^4$, $|\Omega| = 0.53 \text{ fm}^4$. With regard to the simplicity of the whole approach this points towards a very remarkable consistency. However, such a nice agreement does not immediately imply that the mechanisms of meson production in NN-collisions are understood. It may be that the dynamical complexities of such processes reveal themselves only in the more exclusive observables like angular distributions of differential cross sections and asymmetries generated by polarized beams and targets. We hope to report on these topics in the near future.

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